I. INTRODUCTION AND BACKGROUND

LANDFILLS AND LANDFILL METHANE RECOVERY

Sanitary landfilling is the main method of waste disposal in the United States. The EPA estimates about 70% of U. S. municipal solid waste, amounting to about 150 million tons/year over the past decade, is landfilled (Kaldjian, 1990). With conventional landfilling, waste is placed in conformance to existing regulations. Waste deposited in landfills is compacted daily with a soil cover to reduce blowing litter, manage bird and rodent activity, and control odors. This process continues until a planned waste depth is reached. The waste is then covered with an impermeable cover layer, usually clay. In most cases, there is no attempt to manage or monitor conditions within the landfill for biological activity.

PROJECT DESCRIPTION

The objective of this project is the design and construction of two landfill demonstration cells to test the operation of a landfill as a biological treatment system. The landfill environment is manipulated to achieve rapid biological stabilization, accelerating the rate of generation of methane and maximizing gas capture. This will be accomplished through additions and recirculation of liquids (water and leachate) to improve biological reaction conditions in the landfill. Further investigations will include: the potential for landfill leachate treatment through leachate recycle; the extension of landfill life resulting from waste settlement during rapid biological conversion of solid waste to gas and liquid; the assessment of the environmental impacts of the approach in order to provide regulatory agencies with information that can be used to develop guidelines for its application. The monitoring program will provide the data necessary to achieve these objectives. The nature of the monitoring program will allow changes in technique as warranted by ongoing evaluations.

The overall project objectives are as follows:

- The principle project objective is to demonstrate substantially accelerated landfill gas generation and biological stabilization while maximizing landfill gas capture.
- To monitor the biological conditions within the landfill cells.
- To demonstrate that the recirculation of leachate is an effective leachate treatment strategy.
- To demonstrate the landfill life extension that can be realized through more rapid conversion of landfilled solids to gas.
- To provide regulatory agencies with information that can be used to develop guidelines for the application of this technology.

- To better understand the movement of moisture through landfills.

BACKGROUND

Bacterial generation of methane, carbon dioxide, and other trace gases, occurs in almost all landfills containing municipal wastes. Although methane production is significant enough that gas is often usable for energy generation (Augenstein and Pacey, 1992), recovery rates and yields are far under their maximum potential. Maximum methane yield, as demonstrated in laboratory tests, might provide combustible gas having 40 to 50% of the waste's energy content. However only a portion of the methane energy potential is normally realized. Waste decomposition to landfill gas proceeds only slowly, over many decades in conventional, dry landfills. This may be inferred from low gas recovery rates and from recovery of intact, legible reading material after many decades in the landfill (Rathje 1989).

Recovery of landfill gas has been driven by the 1991 Federal Clean Air Act, and by policies of state agencies such as the California Air Resources Board. Of primary interest has been the issue of energy recovery, however, conventional approaches utilizing clay caps and vertical wells are likely to collect between 70 to 90 percent of the gas generated, allowing the remainder to escape to the atmosphere. Reasons for this include:

- Cover porosity. Field experience shows in-place clay final cover to be significantly porous. Augenstein and Pacey (1991) estimate fugitive emissions during operation may be 10 to 60 percent of the gas generated, depending on the site. The California Air Resources Board estimates escape at 40 to 60% of the amount of gas collected (SCM, 1990), which implies fugitive emissions about 30-40% . Walsh estimates fugitive gas per VOC fractions at 25 to 75% (SCS Engineers, 1994).
- Low generation rates. Of methane generated, high fractions can be emitted to the atmosphere at both early and late stages in "conventional" filling. Gas generation may begin, shortly after waste is placed, and before welling can capture gas with high fractional efficiency. At long times after filling and closure, gas generation may continue. Its collection may be less efficient then because continuing collection of low-rate gas generation is less cost effective, and equipment may no longer operate (or may be less well maintained). The amount of gas thus escaping long-term may be considerable; EPA and other models suggest that 20 to 40 percent of total gas generation may occur after 30 year post-closure collection period mandated by the EPA. Thus high collection efficiency of 70 percent or more by a well operated system at peak gas generation rates is reduced by both early and long term fugitive emission when the entire landfill methane generation cycle is considered.

Efficient use of landfill-generated gas is hampered by equipment considerations. To use the gas efficiently, collection and conversion equipment must have capacities which are close to the actual volume of gas produced. Because volume projections may differ from actual results by as much as 50%, selection of appropriate equipment can be difficult.

In summary, methane recovery from landfilled waste is typically less than half of the maximum potential for reasons of inefficient recovery, inability to confidently size equipment to make best use of available gas, and slow and incomplete generation of gas. Conventional landfilling generally results in slow decomposition of wastes over time, and gaseous emissions that are difficult to manage. It also presents various long-term expenses involving gas system and containment maintenance, leachate management, and problems with continuing subsidence. The YCCL Demonstration Project is intended to address these problems.

PAST APPROACHES

Previous attempts to recover methane energy from municipal wastes have involved a variety of waste-to-methane approaches. Early successful solid waste fermentations were conducted in mixed-tank equipment similar to those used to digest sewage solids (Goluecke, 1969, Pfeffer, 1974). However, drawbacks included parasitic energy consumption and high capital equipment costs.

Disadvantages with mixed tank approaches have prompted other work exploring the potential of "static" or unmixed digestion in low-cost reactors which can include landfills (Augenstein et. al., 1976). Calculations of diffusional transport rates, and subsequent laboratory experience, show that waste can be digested without mixing, at high solids levels characteristic of a landfill. In-landfill methane generation has pronounced advantages, namely:

- The reactor is basically "free" in terms of incremental cost
- In-landfill fermentation can easily tolerate inerts (waste components like rocks)
- Laboratory work has shown methane yields comparable to or better than for stirred tank work, so that expensive pre-processing can be avoided.

For these reasons, in-landfill fermentation appears to be the most attractive means of generating methane from municipal wastes, and is currently receiving worldwide attention (Lawson et. al. 1991).

This report presents only a brief background on enhanced landfilling. Readers desiring more background on the subject may refer to the original Proposal to the California Energy Commission (Yolo County, 1991). The following report summarizes various issues involved, and discusses how containment and optimization of biological conditions may be combined to maximize methane recovery.

TRIALS ELSEWHERE

Field trials to accelerate landfill decomposition have already been attempted. It may be useful to briefly review efforts at landfill enhancement that have occurred elsewhere.

- The earliest trial involving detailed measurements of gas generation and other relevant parameters was the field demonstration in Mountain View, CA, in which six cells were operated with a variety of amendments (Pacey et. al., 1987). The test cells were unexpectedly warm (40 °C) at time of construction, possibly due to limited aerobic composting of waste prior to placement of cover soil. Cell temperature continued to rise as methane was generated until several reached temperatures of 50-60 °C, at which time gas generation rates dropped while temperatures remained constant. However, gas production ultimately resumed. Other Mountain View problems included gas leaks, leachate buildup in cells due to inadequate drainage, and various measurement difficulties. Despite problems, this test successfully demonstrated generation rates three to five times that of conventional landfills in the area.
- Tests were conducted at Brogborough, UK, in which 4 cells were used to test the effects of liquid recycle, waste amendments and other variables (Campbell, 1991). Results are difficult to evaluate as cell sizes and contents were approximately doubled two years into the program for reasons having to do with operation of the surrounding landfill. Also, the gas collection efficiency is not well known and may be very poor, as the conventional clay cover is cracked. Failure of temperature probes has also occurred.
- A program was conducted at Binghampton in the early 1980's through the New York State Energy Research and Development Administration (NYSERDA) to test leachate recycle.
- The Delaware Solid Waste Authority (DSWA) is conducting a program wherein two one-acre cells containing 11,000 tons of waste each are testing the effect of leachate recycling. This project has been successful at improving leachate quality and determining liquid retention time in the waste. Waste temperature monitoring has been lost as temperature probes, placed with the waste as it was filled, have failed.

The objectives of earlier trials included waste stabilization, volume reduction, energy recovery, and convenient leachate disposal. Emission abatement had low priority, in part because the environmental impacts of VOC's, particularly methane, had less recognition than currently. The trials have provided some interesting results, but all experienced problems and limitations. Experiences and limitations with these other tests have been considered in planning the YCCL Demonstration project.

Problems with liquid handling occurred at both Mountain View and Brogborough due to design problems and component failure. Difficulties also arose with gas collection, leaks, and measurement of gas flow at Brogborough, Binghampton and for a time, Mountain View.

LANDFILL CONTAINMENT AND MANAGEMENT ISSUES

One general consideration is that any process must be economically compatible with current landfill practice. It must also satisfy present and pending federal/state regulations regarding landfills. The strongest regulatory constraint is that leachate contamination of strata beneath the landfill, or threat of it, must be avoided by appropriate containment and prevention of hydrostatic head on the base liner. Additionally, to maximize gas capture, the landfill surface should be covered by an impermeable membrane.

SURFACE MEMBRANES. Gas recovery efficiency can be greatly improved by use of gas-impermeable membranes. These are coming into wide use (Booth, 1991; Rice, 1994) and may become a post-closure requirement for landfills in the future (Federal Register, June 26, 1992). Synthetic membranes, in contrast to conventional clay caps, have gas permeabilities that are, for practical purposes, negligible. Membranes over gas-conducting layers (such as shredded tires) can capture essentially 100% of gas per VOC's generated. However, such membranes, when used alone, have a serious disadvantage. Surface membranes will maintain waste at low initial moisture levels (20-25%) which simply extends the time for decomposition to as much as a century. Field results have confirmed the substantial slowing of decomposition beneath impermeable membranes (Kraemer, 1993; Leszkiewicz 1995). Such dry containment approaches have been termed "dry tomb" technology (Lee, 1990), and pose the following problems:

- Economics will be very poor for capture and utilization of gas generated at low rates for extremely long periods.
- Membrane and other waste containment integrity must be maintained over longer periods as "entombed" waste decomposes slowly. Leachate generated under such conditions carries a high pollutant load well into the future, incurring high maintenance costs, and liability for groundwater contamination.

Simply covering a landfill with an impermeable membrane will not greatly increase energy recovery, but may create difficulties. To avoid long-term problems associated with conventional landfilling it is also necessary to enhance waste decomposition to speed completion of methane generation. The Yolo County landfill project combines membrane capture with optimization of the methane generation process to complete production within much shorter intervals.

ACCELERATING WASTE DECOMPOSITION AND METHANE GENERATION

Waste decomposition with gas generation can be promoted by control of moisture, temperature, pH management, and nutrients. While other factors can be important, moisture is crucial for biological activities associated with methane generation. Moisture control is the primary method used to enhance generation in this demonstration project, and is the most easily applied enhancement amendment.

Leachate management can be an important major aspect of landfill moisture control. Collection and reinjection of this liquid to the waste mass (commonly referred to as "leachate recycle") is a advocated practice (Pohland, 1989), and could be effective as a means for enhancing methane generation and accelerating stabilization in conventional landfills. However, newer landfills are much deeper and have less permeable covers. Precipitation infiltration, and consequently leachate availability for recycle, is restricted (Leszkiewicz, 1995). Thus, liquid supplements from outside sources may be necessary to increase the moisture content of the waste sufficiently for effective enhancement.

Given measurement limitations in other demonstration projects, a major objective is to instrument and carry out measurements to "fill in the gaps" left by other projects. A key measurement will be that of liquid movement through the cell, providing important information on waste permeability and recoverability of generated gas. Additional measurements include temperature, gas pressure and composition, leachate quality, and containment integrity.

GENERAL APPROACH

The design guidelines adopted for the Yolo County Demonstration Project are as follows:

- To avoid the threat of leachate contamination of underlying strata, the landfill shall have a composite or double base lining, as mandated in all new landfills or landfill expansions.
- To have a highly permeable bottom drainage layer to preclude build up static head.
- Cells shall be filled with waste according to standard landfill practice, except that temporary cover shall consist of materials not restrictive to the flow of liquid. For demonstration purposes, moisture, temperature and pressure sensors shall be placed in the waste to monitor decomposition.
- Temperature, moisture and pressure sensors shall be placed in the waste as the cells are filled in order to monitor processes within the waste mass.
- Provisions for uniform surface liquid addition, such as infiltration trenches, shall be constructed on the surface of the filled waste.
- A porous surface layer, such as shredded tires, shall be placed to create a highly conductive gas collection space for the capture and conduction of gas to collection points.
- Filled cells shall be covered with an impermeable membrane.
- Liquids shall be added as needed to maximize biological activity and gas generation. Liquid addition shall be managed as needed to preclude the development of hydrostatic head on the base liner.

PROJECT PERFORMANCE OBJECTIVES

The project consists of two test cells, each with about 9,000 tons of waste (enhanced cell 8,568 tons and control cell 8,737 tons). These test cells are large enough to represent both the compaction and heat transfer of large-scale landfills at normal waste depth. Techniques to enhance methane production will be applied to one cell (the enhanced cell), with the other serving as the control. The enhanced cell has been provided with means for controlled liquid addition to increase moisture content for methane generation. The cells are instrumented to monitor moisture and temperature at multiple points within the waste. Volume reduction, leachate flow and quality, static head on the base liner, containment integrity and other parameters of interest are also to be monitored. Gas-tight waste containment will allow accurate measurement of methane generation using positive displacement meters.

Performance objectives include:

Estimated Methane Generation: Based on the assumptions stated under heading ENERGY POTENTIAL in Section V, the enhanced demonstration cell is expected to generate about 22.0 million cubic feet of methane, while the control cell is expected to produce only 7.9 million cubic feet. The difference between these values amounts to a net gain of 14.1 million cubic feet of methane, which is the equivalent of 2,430 barrels of oil. These methane volumes should be produced in the enhanced cell within 5 to 10 years of initial liquid addition, whereas, for an unenhanced cell, such gas volumes may take from 30 to 50 years or longer to produce. If decomposition can be brought to completion within 5 years, the average gas flow rate over this period would be about 8 cubic feet per minute, and if the process should reach completion within 1 year (very unlikely rapid decomposition rate), the flow rate would still average to about 42 cubic feet per minute. These flow rates are well within design parameters for pipe size and flow measurement devices.

Volume Reduction and Settlement: The volume reduction brought about by the conversion to methane of the organic fraction of the waste is estimated to account for about 20 to 30 percent of the as-placed volume. The estimated average settlement in the enhanced demonstration cell should be about nine feet, based on a volume reduction of 20 percent. Such settlement corresponds to a recovered landfill volume sufficient to place an additional 1,700 tons of waste.

Water Addition Requirements: The water content of as-placed waste is typically between 20 and 30 percent, and may need to approach 40 to 50 percent for optimal methane-generating conditions. Assuming the initial water content of as-placed waste to be 25 percent, 1 million gallons of water must be added to the enhanced cell to achieve field capacity. Allowing for a transmissivity of 10^{-4} cm per second, water added to the cell should require about 5 months to seep down through the (average) 40 foot depth of waste. The total addition of 1 million gallons of water over a 5 month period dictates a rate of addition of about 10 gallons per minute cumulative for all 14 injection points. The addition of this quantity of water should bring the waste to its field capacity for moisture.

Reduction in Leachate Strength: As water is added beyond field capacity leachate is produced which is collected at the bottom of the cell and recirculated through the waste. After one year of leachate recirculation the following is expected to occur:

- Reduction of Biochemical Oxygen Demand
- Virtually complete elimination of organic acids
- pH brought to near neutrality (6.5 to 8.0)

SUMMARY OF EXPECTED ENERGY BENEFITS

A number of energy, environmental, and landfill operations benefits are expected to result from enhanced landfilling and are summarized below.

- Higher methane yield, higher generation rates, significantly shorter decomposition time.
- Better economics of scale for energy use due to greater quantities of captured gas in significantly shorter time.
- Completion of waste decomposition over shorter terms, reducing long-term risks to the environment and reducing long-term gas collection and other management costs.
- Predictable completion of waste decomposition such that landfill-gas fueled energy equipment may be sized to make maximum use of the gas generated.
- Emission of methane gas into the atmosphere is expected to be virtually eliminated, along with its contribution to global climate change.

SUMMARY OF EXPECTED WASTE MANAGEMENT BENEFITS

- Potential for landfill life extension by volume reduction, and thus, reduced land use.
- Leachate quality improvements and correspondingly reduced threat to groundwater, as well as reduced costs for off-site disposal and treatment.
- Reduced emissions of Volatile Organic Compounds and other air pollutants.
- Reduced costs for post-closure landfill maintenance and gas system operations due to earlier completion of landfill gas generation and waste stabilization.

PROJECT STATUS WITH REGARD TO PERFORMANCE OBJECTIVES WITHIN CEC CONTRACT DOCUMENTS

To date, the Project Objectives, as described in the Project Activities section of the contract with the California Energy Commission, have been achieved. Briefly, these activities include:

Design and Construction of Base Liner: The primary base liner components were designed and constructed as planned. Some of the primary components of the designed system include the following:

- A double composite liner system for the enhanced cell and the single composite liner for the control cell. Current regulations prohibit the introduction of liquids as is required for enhanced landfilling. However, an "engineering alternative" (double composite liner system) to the prescriptive regulations (single composite system) was obtained to demonstrate to the regulatory agencies that benefits can be realized without increasing environmental hazards.

- Leachate collection and removal systems for the cells.
- Perimeter levees for containment of refuse and anchoring the geosynthetic materials.
- Leachate management system.

Construction of the base liner was completed $14,000 below the budget allowance.

<u>Design and Construction of Levees:</u> Construction of the clay levee side walls was conducted while waste was being placed inside and outside of the cell in order to avoid unbalanced loading of the sidewalls. The five-foot lifts of sidewall material and waste were designed to minimize clay use and maximize waste volume. During the winter of 1994, due to reduction of daily waste tonnage and operational difficulties at the landfill, the filling of the demonstration cells was postponed from April of 1994 to April of 1995. A contractor was chosen on a time-and-materials basis which resulted in a substantial increase in the cost of construction. The original construction estimate of $40,000 was amended to $106,000, and an additional $14,000 was expended to construct the instrumentation and gas collection risers within the waste mass. The new contractor completed this $120,000 phase of the project. Part of the added cost was covered by a grant from the California Integrated Waste Management Board.

<u>Design and Construction of The Waste Monitoring System:</u> Thermistor type temperature sensors, custom-made PCV moisture sensors, and agricultural soil moisture sensors were selected and installed within both demonstration cells. The control cell contains 11 temperature and 19 moisture sensors, while the enhanced cell is equipped with 13 temperature sensors and 37 moisture sensors. Wire leads from the sensors were enclosed in a housing of nylon-reinforced flexible PVC tubing for protection against damage. Additional slack was provided for these leads to prevent breakage as settlement occurred. A Druck pressure transducer was placed within the leachate collection trench to measure hydrostatic head above the base liner. All wire leads were connected to a Micrologger and a remote transmitting unit. Construction of the waste monitoring system was completed within budget.

<u>Design and Construction of Landfill Gas Collection and Removal System:</u> Vertical and horizontal gas collection systems were designed and constructed. The vertical gas wells in each cell were constructed of perforated 4-inch diameter PVC pipes; one well in each cell surrounded by gravel and the other by shredded tires enclosed in wire mesh. The horizontal gas collection system was constructed from the surface of the waste upward, beginning with a perforated 4-inch diameter PVC pipe placed within a compressed layer of shredded tires at least one foot thick. A protective, 12 oz. per square foot geotextile layer was placed above the shredded tires followed by a compacted layer of clay 1.5 feet thick. All of this was finally covered with a 40 mil, linear low density polyethylene (LLDPE) impermeable membrane. Gas can be extracted either by the vertical or horizontal pipe system, or by a combination of both.

The gas removal system was designed and constructed to handle a volume flow rate much higher than that which is to be expected from these cells. The gas is conducted from the cells to the power plant via a 6-inch diameter PVC pipe. Landfill gas flowing from each cell is measured separately by a positive displacement rotary gas meter installed after the condensate knockout and trap system. Each meter is capable of measuring flows from 42 cubic feet per hour to 5,000 cubic feet per hour. The condensate that drains from the knockout and main 6-inch header is collected disposed of in the landfill leachate management system. The gas recovery system was constructed within budget.

Design and Construction of Leachate Recirculation and Pumping System: The leachate recirculation and pumping system was designed to collect and distribute liquid within the enhanced cell. The primary components include the following:

- A leachate pumping system capable of pumping a maximum of 12 gallons per minute.
- A leachate flow metering system for both cells.
- A pipe system to conduct leachate to the holding tank and back to the cells.
- A distribution system for the enhanced cell.

The distribution system in the enhanced cell consists of 14 injection points distributed over the waste, below the surface membrane, 20 feet apart on center. Liquid will be injected to each point at a rate of about 0.71 gallons per minute per injector for a total of 10 gallons per minute. Each injection point has a measuring instrument to determine the depth of liquid on the waste surface, which is recorded automatically. It was initially anticipated that if the average depth of half the injection points were greater than a preset depth, the pump would automatically shut off until the liquid level had declined to an acceptable level. However, this leachte inflow management plan was abondoned to preserve memory in the datalogger for other data measurements considered to be more important. The liquid depth sensors are still used to monitor liquid depths in the infiltration trenches but are not used to control the pumping of liquid to the enhanced cell. This system was constructed within budget.

Design and Construction of the Cover System: A composite liner system was designed and constructed for the final cover for both cells. The LLDPE liner system was not covered with soil as originally intended. This was intended for ease of inspection and any repairs that might be required. The liner was weighted down with sand bags. The pressure under the liner will be controlled so that no billowing of the liner will occur. As an extra precaution, rubber blow-out caps were installed to relieve pressure build up in case the automatic pressure adjustment system fails. A porous layer of shredded tires was used instead of drain rock for gas collection with a geotextile to protect the liner. In December of 1995, during the construction of the LLDPE liner, a windy storm occurred which damaged the liner resulting in $20,000 in repair costs. Yolo County's insurance company covered some of the cost incurred, though $5,000 had to be paid out of the contingency portion of the contract. Excepting this unavoidable cost, the cover system was completed within budget.

Although module construction, cell construction and all subsequent steps were delayed, all major project tasks have been accomplished. The original CEC funded portion of the project has brought the cells to the point of operation.

We have accomplished the steps necessary to arrive at the fundamental purpose of the project, namely, to apply enhanced landfill techniques to a waste management unit in order to accelerate the stabilization of the waste and monitor effects within the waste.

Liquid addition to the enhanced cell and the application of a vacuum to both the enhanced and control cells to collect lndfill gas occurred in October, 1996. Preliminary data is presented elsewhere in this report.